Development of an Optical Repeater System for Pagers and Cellular Phones

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ABSTRACT An optical repeater system has been developed that provides pager and cellular phone services in an underground parking garage, where such services were unavailable. The transmitter uses the multi-coupler method which reduces the cost of equipment and diminishes the number of fibers. Use of a low-noise, low-distortion 1.3-μm distributed feedback laser provides high system performance.

Out- and indoor radio transmission design was carried out and the system's feasibility was tested by installation in an underground parking garage. This paper reports on equipment design and radio transmission design.

1. INTRODUCTION

There has been remarkable growth in Japan's mobile communications market, with the number of subscribers reaching some 45 million at the end of 1998. This has created a need for services that extend to locations that were previously blind spots for pagers and cellular phones.

To address this need the advantages of systems using analog optical transmission have been recognized in terms of flexibility in cable laying design, lower costs of installation, and broader service area. Furukawa Electric has therefore developed an N-to-one system using the optical multi-coupler method, involving less equipment and lower cost than conventional systems in which optical transmitters are connected one-to-one.

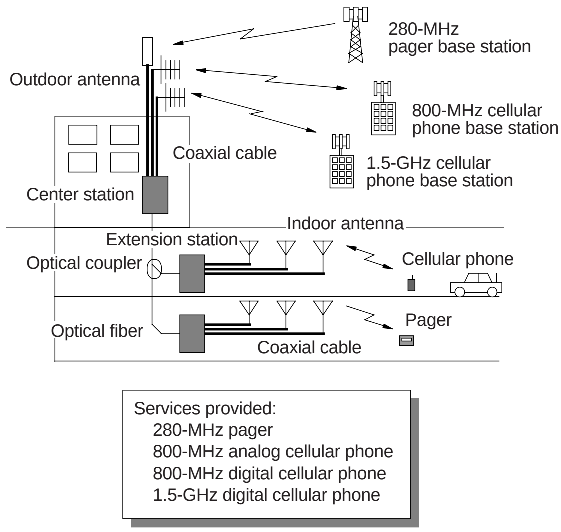

Figure 1 Schematic image of the system

2. SYSTEM CONFIGURATION

Figure 1 is a schematic image of the system, showing the nature of the services provided.

The system comprises an outdoor antenna, a central station, extension stations and indoor antennas. It relays all pager and cellular phone services, making them available within the underground parking garage.

In the downstream link of the system, the signals for pagers, 800-MHz cellular phones and 1.5-GHz cellular phones that are transmitted from the base station are received by the outdoor antenna installed for each waveband and converted into optical signals at the central station using direct intensity modulation. They are then transmitted through a single-mode (SM) optical fiber and optical couplers to the extension stations installed in the parking garage. The extension station then converts the optical signals into RF signals, amplifies them, and radiates them over the indoor antennas in the parking garage. The indoor antennas, like the outdoor antenna, are installed for each frequency band.

In the upstream link, on the other hand, signals generated by cellular phones in the parking garage are received by the indoor antennas and converted by the extension stations into optical signals. The signals from each of the extension stations are combined by an optical coupler into a single SM fiber. The central station converts the optical

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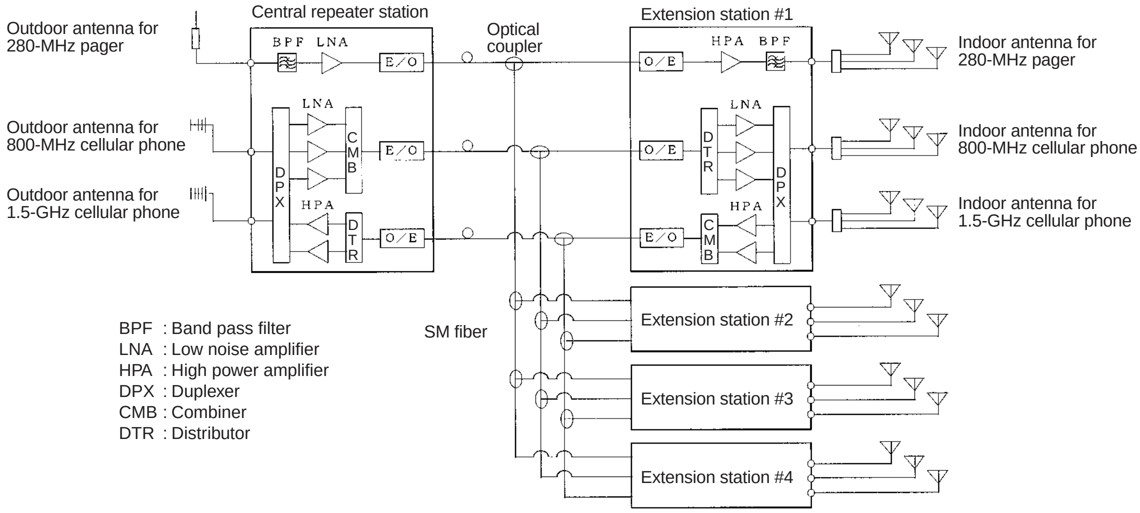
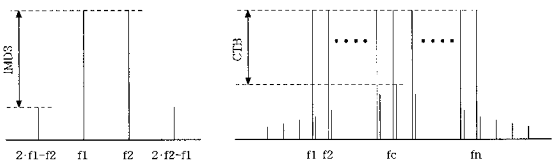


Figure 2 System configuration



a) Generation of distortion by 2 carriers

b) Generation of distortion by multi-carriers

Figure 3 Relationship of plural carriers and distortion

Table 1 Distribution of C/N and IMD3

	Low noise amplifier	Optical transmitter	High power amplifier	Total
Downstream C/N (dB)	67	62	70	60
IMD3 (dBc)	-110	-80	-85	-75
Upstream C/N (dB)	80	70	70	66
IMD3 (dBc)	-70	-64	-64	-56

signals from the extension stations into RF signals, amplifies them and sends them from the outdoor antenna to the base station of each cellular phone service.

Figure 2 shows the configuration of the pager system and of the cellular phone system, the optical transmitter of which multiplexes the 800-MHz and 1.5-GHz signals.

The optical transmitter uses a multi-coupler method which uses an optical coupler for branching or combining. The lasers are low-noise, low-distortion 1.3-μm distributed feedback (DFB) laser diodes, and PIN photodiodes are used as photodetectors because of their good linearity.

In the upstream links particularly, care is taken that the difference in wavelength between the laser diodes in each of the extension stations does not overlap with the RF band of the cellular phones, and by providing stable control, a single optical fiber can be connected to up to four extension stations.

At the input of both the downstream and upstream links, a low-noise amplifier (LNA) is used to inhibit the generation of noise and amplify to the level required by the electro-optical converters (E/O). A Class A high-power amplifier (HPA) having a high intercept point (ICP) is used at the antenna output to inhibit the generation of third intermodulation distortion (IMD3).

3. GENERAL DESCRIPTION OF THE EQUIPMENT

3.1 Characteristics Distribution

In the distribution of characteristics to the LNA, optical converter (E/O, O/E) and HPA, C/N distribution was done using

$$C/N_{total}=10\log\{10^{-\frac{C/N_{LNA}}{10}}+10^{-\frac{C/N_{opt}}{10}}+10^{-\frac{C/N_{HPA}}{10}}\}^{-1}\ [\mathrm{dB}] \quad .....(1)$$

and IMD3 distribution using

$$IMD3_{total}=20\log\{10^{(\frac{IMD3_{LNA}}{20})}+10^{(\frac{IMD3_{opt}}{20})}+10^{(\frac{IMD3_{HPA}}{20})}\ [\mathrm{dBc}] \quad .....(2)$$

In the system design adopted here, the number of carriers aligned at equal frequency spacing was 60 for downstream links and 8 for upstream.

As Figure 3 shows, composite triple beat (CTB) distortion generated by multi-carriers produces more distortion than the IMD3 generated by two carriers and distortion output is also greater. When 60 carriers are transmitted at equal-frequency spacing in the downstream link, the CTB level becomes 37.1 dB larger than IMD3 on the condition that output per carrier is constant and irrelevant to the phase of distortion. Similarly, the increase in the upstream links is 17.8 dB[1]. Table 3 shows the characteristics distribution for cellular phone service in this system, where distortion is converted from CTB to IMD3.

3.2 Optical Transmitter Section

This system makes use of: 1) both subcarrier transmission technology, in which frequency-multiplexed RF signals undergo direct intensity modulation by the laser diode of the E/O converter and are demodulated again to the original RF signal by the photodetector of the O/E converter; and 2) the optical multi-coupler method, in which optical signals are branched and combined by the optical coupler. In subcarrier transmission, no RF-band modem is required, and the optical multi-coupler system makes possible a reduction in the number of E/O and O/E converters, and in the number of optical fibers used. The combination of the two technologies improves efficiency and lowers cost.

For cellular phone service, the 800-MHz and 1.5-GHz signals are multiplexed for transmission.

To achieve the multi-carrier transmission characteristics described in Section 3.1 above, the E/O converters in the upstream and downstream links have 1.3-μm DFB laser diodes suited to analog transmission having low distortion characteristics.

The C/N of the optical transmitter may be found by

$$C/N_{opt}=10\log\frac{(m\cdot S\cdot P)^2}{2\cdot\{I_{th}{}^2+2\cdot e\cdot S\cdot P+(S\cdot P)^2\cdot RIN\}\cdot B}[dB] \quad \text{.............. (3)}$$

where:
m is the modulation depth (true value),
I_{th} is the equivalent input noise current density (A/Hz$^{1/2}$),
P is the optical receiving level of the photodiode (W),
S is the optical sensitivity of the photodiode (A/W),
B is the noise bandsidth (Hz) and
e is the quantum of electricity.

The IMD3, for its part, is found by

$$IMD3_{opt}=IMD3_{LD}+2\cdot 20\log(m_{opt}/m_{LD})[dBc] \quad \text{.....(4)}$$

where: m_{LD} and $IMD3_{LD}$ are the modulation depth and distortion of the laser diode, and m_{opt} and $IMD3_{opt}$ are the modulation depth and distortion in this system.

The C/N and IMD3 characteristics of the optical transmitter are in a tradeoff relationship with optical modulation depth m. As an illustration, Figure 4 plots C/N and IMD3 against modulation depth for downstream links.

To inhibit the generation of distortion of the signal itself, a region must be used in which optical modulation depth is not overmodulated by multi-carrier transmission.

From these conditions, a modulation depth m_{opt} of 2.6 for downstream links and 21.0% for upstream links was used respectively.

When, on the other hand, optical signal is multiplexed in downstream links, beat noise occurs at the frequency of the difference between laser diode wavelengths. If the original RF signal is being modulated, chirping will occur and the beat noise band will become broader. In this system when these beat noises overlap the RF signal band for cellular phones, nominal RIN deteriorates, that is to say the possibility of deterioration in system C/N arises. It is known that if beat noise is separated to some degree from the signal band its influence on RIN virtually disappears[2]. In this system this point was fully considered in selecting the lasing wavelength of the laser diodes, and automatic power control (APC) and automatic temperature control (ATC) circuits are provided to stabilize the lasing wavelength.

By this means it is possible to connect up to four extension stations per optical fiber.

3.3 Amplifier Section

In both the upstream and downstream links, a low-noise amplifier (LNA) is used for the first-stage amplifier that amplifies the RF signal received by the antenna to the level required for optical modulation, and a high-power amplifier (HPA) having a high ICP is used for the amplifier that amplifies the RF signal demodulated from the optical

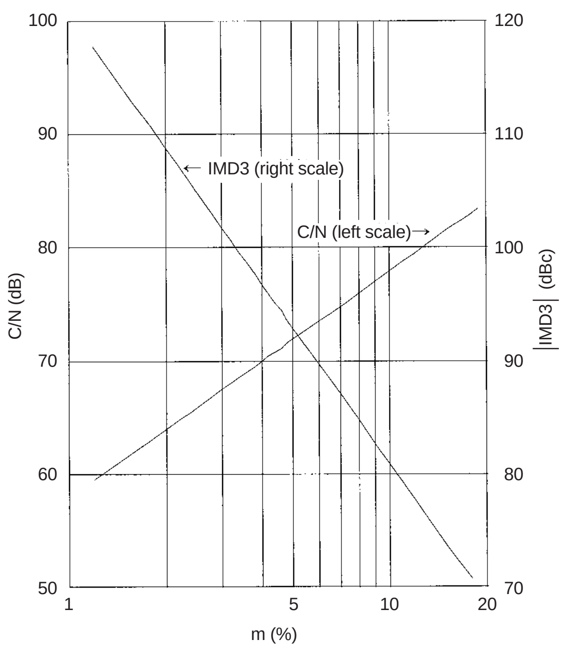


Figure 4 C/N and IMD3 vs. modulation depth

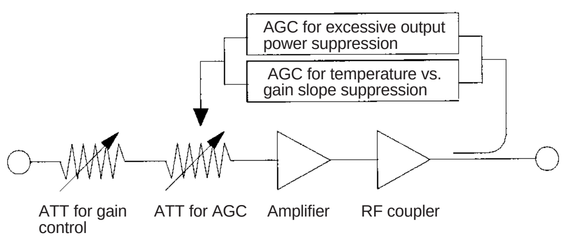


Figure 5 Block diagram of HPA

signal to the level required for radiation via the antenna. To inhibit generation of IMD3, all amplifiers use a region of good linearity in A-class operation and are provided with a variable attenuator for gain control.

The relationship among the ICP (dBm), signal output power P_{out} (dBm) and IMD3 (dBc) for the amplifiers may be expressed by

$$ICP = \frac{|IMD3|}{2} + P_{out} \quad \text{....................(5)}$$

allowing the ICP required for the amplifier to be selected.

Figure 5 is a block diagram showing the structure of the HPA, which comprises an automatic gain control (AGC) for output power suppression and an AGC for temperature compensation, configured using the same feedback circuit. The output power suppression AGC acts when input is excessive to produce a constant output, and is also provided with the function of interrupting the amplifier power supply when further excessive input occurs, preventing the radiation of spurious radio waves.

Figure 6 shows the relationship between ambient temperature and gain. The AGC has resulted in stable gain and has stabilized the output.

3.4 Alarm Section

Alarms between the central station and the extension stations are transmitted on a twisted pair with RS-485. The extension stations are polled from the central station, and once data on the amplifier faults, optical device faults, power supply faults, etc. for each of the central station's extension stations has been gathered, it is connected by relay contacts to the fire prevention center within the building.

4. TRANSMISSION CHARACTERISTICS

Table 2 shows the system specifications, which defines spurious emissions including IMD3. Photo 1 shows the

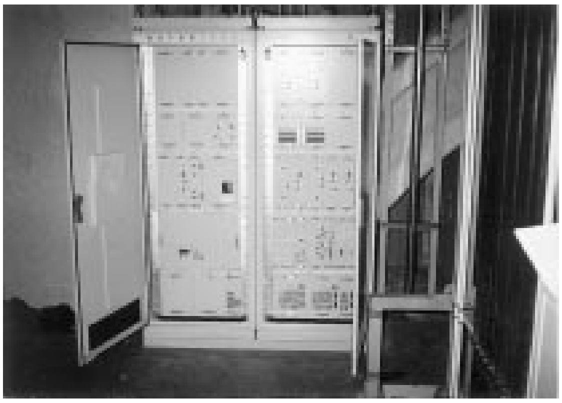


Photo 1 Appearance of central repeater station

Table 2 System specifications

Item	Specification	
	Upstream	Downstream
Pager Frequency band	—	276~288MHz
No. of transmit carriers	—	70
Device output	—	0 dBm/carrier
800-MHz cellular phone Frequency band	915~940MHz 940~958MHz	810~828MHz 860~885MHz
No. of transmit carriers	8	104
Device output	16 dBm/carrier	7 dBm/carrier
1.5-GHz cellular phone Frequency band	1,429~1,453MHz	1,477~1,501MHz
No. of transmit carriers	8	60
Device output	16 dBm/carrier	7 dBm/carrier
C/N	60 dB or better (signal bandwidth 32 kHz)	
Spurious radiation	25 μW or less	
No. of extension station	Max. 4	
Transmission range	Max. 1 km	
Operating ambient temp.	0~40˚C	
Overall dimensions (W x H x D)	1,140x1,625x550 mm (central and extension stations)	

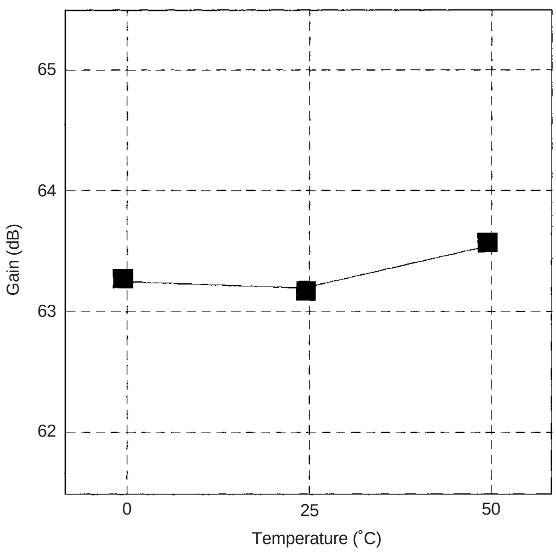


Figure 6 Gain stability of HPA for 1.5-GHz band

appearance of the central repeater station. Extension stations have a similar appearance. Figure 7 shows the temperature dependence of C/N and IMD3 for 1.5-GHz-band system, as representative of the temperature characteristics of the system. All transmission characteristics, including these, meet the desired quality levels.

Photo 2 Outdoor antennas for base station (from top in order: sleeve antenna for 280-MHz pager, Yagi antenna with radome for 800 MHz, Yagi antenna with radome for 1.5 GHz, 2-tier stacked Yagi antenna with radome for 800 MHz band)

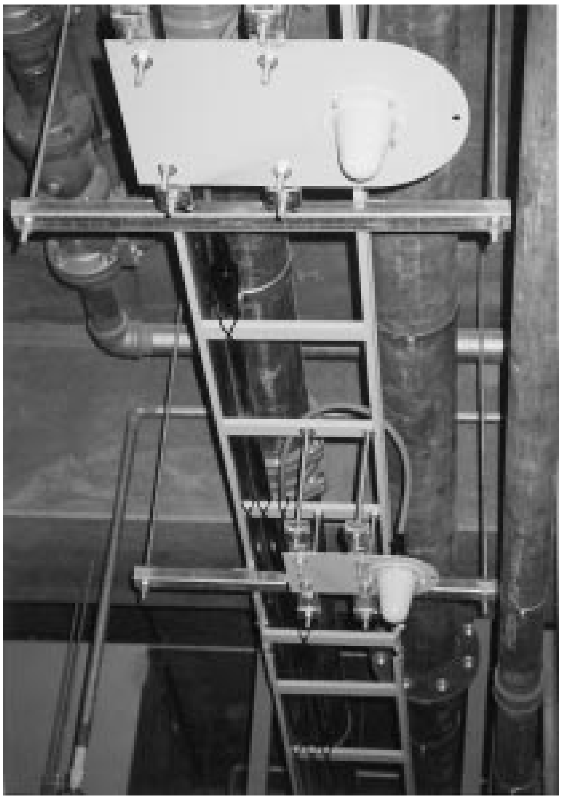


Photo 3 Indoor antennas for mobile stations (from front in order: monopole antenna with radome for 800 MHz band, monopole antenna with radome for 1.5 GHz)

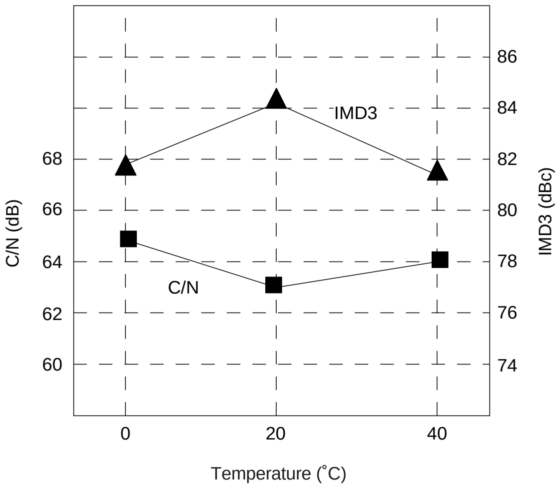


Figure 7 Temperature dependence of C/N and IMD3 for 1.5-GHz-band system

5. RADIO TRANSMISSION DESIGN

In installing the system in the underground parking garage a process of radio transmission design was undertaken.

Photo 2 shows the disposition of the antennas for the base station. Taking into account the location and distance of each service and antenna directivity, it was possible to receive from and transmit to 10 services with these four antennas. This represents a significant saving in terms of the number of antennas compared to dedicating one to each service and does not detract from the appearance of the building.

Photo 3 shows the indoor antennas for cellular phones mounted in the parking garage.

Analysis of signal propagation in the parking garage was performed using free space propagation loss. The garage contained a variety of obstacles that increased losses, however, such as partitions, corners and parked vehicles. Losses were standardized based on experimental data on these increases, and a calculation of propagation losses was performed. Taking the requisite reception level for each service as 30 dBμV/m for pagers[3] and -98 dBm for cellular phones[4], and using the radiated power of the antennas and the above calculation of propagation loss, it was decided to install three indoor antennas on each floor to assure reception of all services throughout the parking garage.

Table 3 shows the reception level for cellular phones at the numbered points within the parking garage shown in Figure 8. Measured values obtained were substantially the same as the calculated values, and although, due to the effect of the surroundings, some were as much as 10 dB lower, the reception level for the mobile stations was found to be adequate at all points measured.

Thus superior reception quality in the underground parking garage was confirmed.

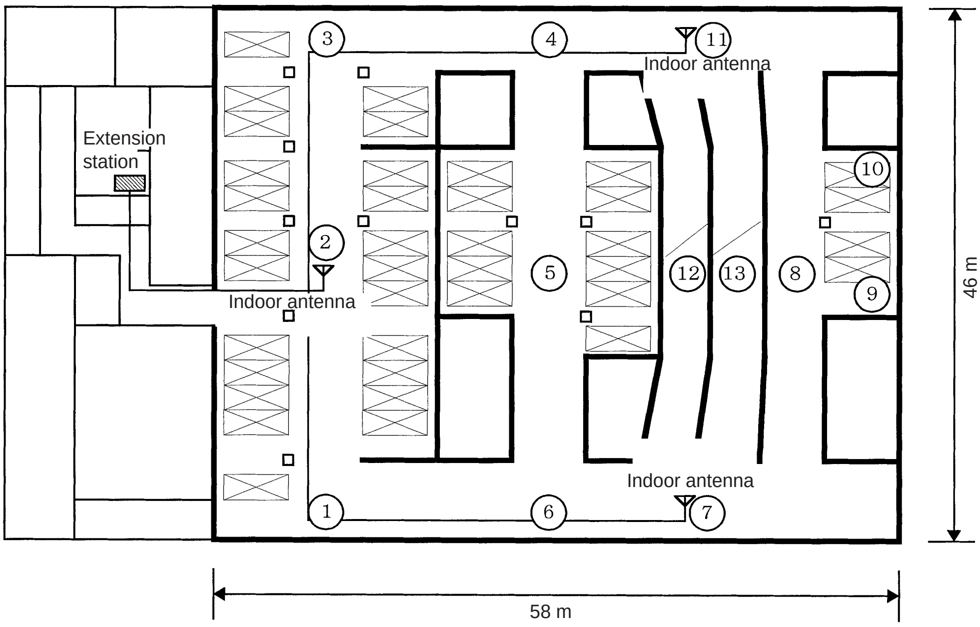


Figure 8 Measurement points in underground parking garage

Table 3 Received power of dipole antenna in underground parking garage (in dBm) at numbered points

	800-MHz band		1.5-GHz band	
Measurement point (see Figure 8)	Calculated value [dBm]	Measured value [dBm]	Calculated value [dBm]	Measured value [dBm]
①	-56	-59	-61	-62
②	-38	-46	-43	-51
③	-56	-59	-61	-71
④	-56	-58	-60	-64
⑤	-73	-78	-78	-80
⑥	-56	-57	-60	-59
⑦	-38	-55	-43	-51
⑧	-72	-73	-76	-83
⑨	-83	-82	-88	-89
⑩	-81	-77	-86	-87
⑪	-38	-42	-43	-46
⑫	-60	-64	-64	-71
⑬	-60	-50	-64	-62

6. CONCLUSIONS

Through the use of optical multi-couplers it has been possible to develop a repeater system for pagers and cellular phones in an underground parking garage that has lower equipment costs and reduces the number of optical fibers. Radio transmission design was carried out, enabling in-the-field use of all pagers and cellular phones.

It is intended to proceed with the development of compact wall-mounted equipment.

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